

BABAR Resonance and Four-quark Mesons *

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The new narrow resonance which has been observed at the B factories is assigned to the $I_z = 0$ component, \hat{F}_I^+ , of iso-triplet charmed four-quark mesons, and as its consequence, existence of additional narrow resonances in different channels is predicted.

Recently the BABAR Collaboration [1] has observed a narrow $D_s^+ \pi^0$ resonance with a mass 2317.6 ± 1.3 MeV and a width 8.8 ± 1.1 MeV (a Gaussian fit but the intrinsic width $\lesssim 10$ MeV), which has been confirmed by the CLEO[2] and the BELLE collaboration[3], and suggested that it is a scalar four-quark meson.

Four-quark mesons can be classified into four types [4], $\{qq\bar{q}\bar{q}\} = [qq][\bar{q}\bar{q}] \oplus (qq)(\bar{q}\bar{q}) \oplus \{[qq](\bar{q}\bar{q}) \pm (qq)[\bar{q}\bar{q}]\}$, where parentheses and square brackets denote symmetry and anti-symmetry, respectively. The first two on the right-hand-side can have $J^{P(C)} = 0^{+(+)}$. Each of them is again classified into two classes (*heavier* and *lighter* ones) because of two different ways to produce color singlet states. We discriminate these two by putting * on the former in accordance with Ref. [4] in which the four-quark mesons were studied within the framework of $q = u, d$ and s .

In this report, however, we extend the above framework straightforwardly to $q = u, d, s$ and c , and concentrate on the $[cq][\bar{q}\bar{q}]$ mesons with $q = u, d, s$. (For more details and notations, see Ref. [5].) The masses of the $[cq][\bar{q}\bar{q}]$ mesons are now crudely estimated by using a simple quark counting with $\Delta m_s = m_s - m_n \simeq 0.1$ GeV, ($n = u, d$), at ~ 2 GeV scale and the measured $m_{\hat{F}_I} = 2.32$ GeV as the input data. [We will assign the new resonance to \hat{F}_I^+ later.] The estimated mass values are listed in Table I. The masses of the lighter $[cq][\bar{q}\bar{q}]$ are close to the thresholds of two body decays through strong interactions. In addition, from the crossing matrices of four-quark states for the color and the spin [4], it is seen that the probability to find the colorless “ D_s^+ ” and “ π^0 ” in the \hat{F}_I^+ is rather small. Therefore, the rate for the $\hat{F}_I^+ \rightarrow D_s^+ \pi^0$ can be small as the new resonance, although it can decay through iso(I)-spin conserving interactions. Since some of the $[cq][\bar{q}\bar{q}]$ mesons are not massive enough to decay into two pseudoscalar mesons through I -spin conserving interactions, their dominant decays may be I -spin non-conserving ones unless their masses are higher than the expected ones.

Table I. Ideally mixed scalar $[cq][\bar{q}\bar{q}]$ mesons (with $q = u, d, s$), where S and I denote the strangeness and the I -spin.

S	$I = 1$	$I = \frac{1}{2}$	$I = 0$	Mass(GeV)
1	\hat{F}_I \hat{F}_I^*		\hat{F}_0 \hat{F}_0^*	2.32(†) (3.1)
0		\hat{D} \hat{D}^* \hat{D}^s \hat{D}^{s*}		2.22 (3.0) 2.42 (3.2)
-1			\hat{E}^0 \hat{E}^{0*}	2.32 (3.1)

(†) : Input data

Now we study numerically decays of the $[cq][\bar{q}\bar{q}]$ mesons by assigning the new resonance to \hat{F}_I^+ , although there exist many proposals to assign it to the other hadron states such as a (DK) molecule [6] (or atom [7]), an iso-singlet four-quark meson [8], a 3P_0 ($c\bar{s}$) state [9], a chiral partner of D_s^+ [10], a mixed state of a scalar four-quark and a ($c\bar{s}$) state [11], etc. Consider, as an example, a decay, $A(\mathbf{p}) \rightarrow B(\mathbf{p}') + \pi(\mathbf{q})$, where A , B and π are a parent scalar, a daughter pseudoscalar and a π meson, respectively. The rate for the decay is given by

$$\Gamma(A \rightarrow B\pi) = \frac{q_c}{8\pi m_A^2} |M(A \rightarrow B\pi)|^2, \quad (1)$$

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where q_c and $M(A \rightarrow B\pi)$ denote the center-of-mass momentum of the final mesons and the decay amplitude, respectively. To calculate the amplitude, we here use the PCAC hypothesis and a hard pion approximation in the infinite momentum frame (IMF), i.e., $\mathbf{p} \rightarrow \infty$ [12]. In this way, the amplitude is given approximately by

$$M(A \rightarrow B\pi) \simeq \left(\frac{m_A^2 - m_B^2}{f_\pi} \right) \langle B | A_\pi | A \rangle, \quad (2)$$

where A_π is the axial counterpart of the I -spin. *Asymptotic matrix elements* of A_π can be parameterized by using *asymptotic flavor symmetry*. (Asymptotic symmetry and its fruitful results were reviewed in Ref. [12].) Although asymptotic matrix elements including the four-quark states have been parameterized previously [13, 14, 15], we here list the related ones,

$$\begin{aligned} \langle D_s^+ | A_{\pi^-} | \hat{F}_I^{++} \rangle &= \sqrt{2} \langle D_s^+ | A_{\pi^0} | \hat{F}_I^+ \rangle = \langle D_s^+ | A_{\pi^+} | \hat{F}_I^0 \rangle \\ &= -\langle D^0 | A_{\pi^-} | \hat{D}^+ \rangle = 2 \langle D^+ | A_{\pi^0} | \hat{D}^+ \rangle \\ &= -2 \langle D^0 | A_{\pi^0} | \hat{D}^0 \rangle = -\langle D^+ | A_{\pi^+} | \hat{D}^0 \rangle. \end{aligned} \quad (3)$$

Inserting Eq.(2) with Eq.(3) into Eq.(1), we can calculate the approximate rates for the allowed two-body decays. Here we equate the calculated width for the $\hat{F}_I^+ \rightarrow D_s^+ \pi^0$ decay to the measured one, i.e., $\Gamma(\hat{F}_I^+ \rightarrow D_s^+ \pi^0) \simeq 8.8$ MeV, since we do not find any other decays which can have large rates, and use it as the input data when we estimate the rates for the other decays. The results are listed in Table II. All the estimated partial widths of \hat{F}_I and \hat{D} are lying in the region, 4.5 – 9.0 MeV, so that they will be observed as narrow resonances in the $D_s^+ \pi$ and $D\pi$ channels, respectively. The $\hat{D}^s \rightarrow D\eta$ decays are approximately on the threshold, i.e., $m_{\hat{D}^s} \simeq m_D + m_\eta$, so that it is not clear if they are kinematically allowed. Besides, the decay is sensitive to the η - η' mixing scheme which is still model dependent [16]. Therefore, we need more precise and reliable values of $m_{\hat{D}^s}$, η - η' mixing parameters and decay constants in the η - η' system to obtain a definite result.

\hat{F}_0^+ cannot decay into $D_s^+ \pi^0$ as long as the I -spin is conserved, so that it will decay dominantly through I -spin non-conserving interactions.

$\hat{E}^0 \sim [cs][\bar{u}d]$ is an iso-singlet scalar meson with $C = 1$ and $S = -1$. It cannot decay into $D\bar{K}$ final states unless it is massive enough. If its mass is of almost the same as the \hat{F}_0^+ , then it cannot decay through strong interactions or electromagnetic interactions [17, 18] since no ordinary meson with $C = 1$ and $S = -1$ exists. Therefore, if it can be created, it will have a very long life.

Table II. The assumed dominant decays of scalar $[cq][\bar{q}\bar{q}]$ mesons and their estimated widths. $\Gamma(\hat{F}_I^+ \rightarrow D_s^+ \pi^0) = 8.8$ MeV is used as the input data. The decays into the final states between the angular brackets are not allowed kinematically as long as the parent mass values in the parentheses are taken.

Parent (Mass in GeV)	Final State	Width (MeV)
$\hat{F}_I^{++}(2.32)$	$D_s^+ \pi^+$	8.8
$\hat{F}_I^+(2.32)$	$D_s^+ \pi^0$	
$\hat{F}_I^0(2.32)$	$D_s^+ \pi^-$	
$\hat{D}^+(2.22)$	$D^0 \pi^+$	9.0
	$D^+ \pi^0$	4.5
$\hat{D}^0(2.22)$	$D^+ \pi^-$	9.0
	$D^0 \pi^0$	4.5
$\hat{D}^s(2.42)$	$D\eta$	–
$\hat{F}_0^+(2.32)$	$< D_s^+ \eta >$	–
	$D_s^+ \pi^0$	(I -spin non-cons.)
$\hat{E}^0(2.32)$	$< D\bar{K} >$	–

In summary we have studied the decays of the scalar $[cq][\bar{q}\bar{q}]$ mesons into two pseudoscalar mesons by assigning the BABAR resonance to \hat{F}_I^+ (in our notation) and assuming the I -spin conservation. All the allowed decays are not very far from the corresponding thresholds so that their rates have been expected to saturate approximately their total widths. \hat{F}_I and \hat{D} could be observed as narrow resonances such as the BABAR one. To distinguish the present assignment from the other models and to confirm it, therefore, it is important to observe these narrow resonances.

Although we have not studied numerically the $\hat{D}^s \rightarrow D\eta$, we can qualitatively expect that \hat{D}^s will be much narrower than \hat{F}_I and \hat{D} . \hat{E}^0 will decay through weak interactions if it is created as long as its mass is below the $\hat{E}^0 \rightarrow D\bar{K}$ threshold.

If the existence of four-quark mesons is confirmed, it will be very much helpful to understand hadronic weak decays of the K and charm mesons. The existence of the heavier class of $[qq][\bar{q}\bar{q}]$ and $(qq)(\bar{q}\bar{q})$ mesons leads to a solution to the long standing puzzle in the charm decays [19], $\Gamma(D^0 \rightarrow K^+K^-)/\Gamma(D^0 \rightarrow \pi^+\pi^-) \simeq 3$, in consistency with the other two-body decays of the charm mesons [13, 14, 15]. Besides, the lighter $(qq)(\bar{q}\bar{q})$ mesons are useful to understand the $|\Delta\mathbf{I}| = 1/2$ rule violating $K \rightarrow \pi\pi$ decays in consistency with the $K \rightarrow \pi\pi$ decays satisfying the $|\Delta\mathbf{I}| = 1/2$ rule, the K_L - K_S mass difference, the $K_L \rightarrow \gamma\gamma$ and the Dalitz decays of K_L [20].

Therefore, it is very much important to confirm the existence of the four-quark mesons not only in hadron spectroscopy but also in hadronic weak interactions of the K and charm mesons.

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